Surface plasmon tunable filter and spectrometer-on-a-chip

Yu Wang
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

S. D. Russell
Naval Command Control and Ocean Surveillance Center, RDTE Division, Advanced Technology Branch, Code D853, San Diego, CA 92152-5732

R. L. Shimabukuro
Naval Command Control and Ocean Surveillance Center, RDTE Division, Integrated Circuit Research and Fabrication Branch, Code D893, San Diego, CA 92152-7633

Surface plasmon tunable filter (SPTF) is a new technology invented in Jet Propulsion Lab. When a white light is incident on a metal/air/metal structure, in certain condition, surface plasmon waves can be excited at one metal/air material interface; those photons in surface plasmon resonance wavelength range will be converted into the energy of free electrons in the metal than coupled into the other metal film, and re-radiate out the color light. This surface plasmon resonance depends on the dielectric constant of the metal and the thickness of the air gap; when the thickness of the air gap changes, the surface plasmon resonance spectrum can be shifted form one wavelength to the other, and this is a tunable filter.

SPTF is a light weight, low power device, it can be integrated with a solid state image sensor to form a spectrometer-on-a-chip. Theoretical calculation has shown that this image spectrometer can also work in IR range up to at least 10 μm.

Keywords: Surface plasmons, tunable filter, electro-optics, thin film, spectrometer

An image spectrometer acquires images of the same scene simultaneously in many contiguous spectral bands over a given spectral range. By adding wavelength to the image as a third dimension, the spectrum of any pixel in the scene can be calculated. These images can be used to obtain the reflectance spectrum for each image pixel, which can be used to identify components in the target.

The most common method of doing image spectroscopy is by changing fixed dichroic filters, the system is heavy and the speed is slow. Several tunable filters have been proposed, but they all have sever problems, for example, the acousto-optic tunable filter is power hungry (in kilowatts), the liquid crystal tunable filter is slow and has low efficiency. Now a new technology of surface plasmon tunable color filter has been invented at JPL, surface plasmon tunable filter is a light weight, low power, high efficiency device, it can be integrated with a solid state sensor form an imaging spectrometer on a chip.

The surface plasmon (SP) has been studied since the 1960's. It can be described as a collective oscillation in electron density at the interface of a metal and a dielectric*. At SP resonance, the reflected light vanishes. This resonance is referred to as attenuated total reflection, and is dependent upon the dielectric constants of both the metal and the dielectric. If an electro-optical (EO) material is used as the dielectric and a voltage is applied to change the SP resonance condition, the reflected light can be modulated[2,3]. A SP spatial laser light modulator with a contrast ratio greater than 100 has been reported[4].

If we consider the SP light modulator in frequency space, the photons at the SP resonance frequency will be absorbed by the free electrons in the metal, and the photons away from the SP resonance will be totally reflected. If a voltage is applied to the EO material, the resonance frequency will change, and a tunable filter is formed.

The SP tunable notch filter[5] was invented in 1992, and a prototype model was built in 1993. The experimental result was published in 1995 as a new physical phenomenon of "voltage-induced color-selective absorption with surface plasmons"[6].

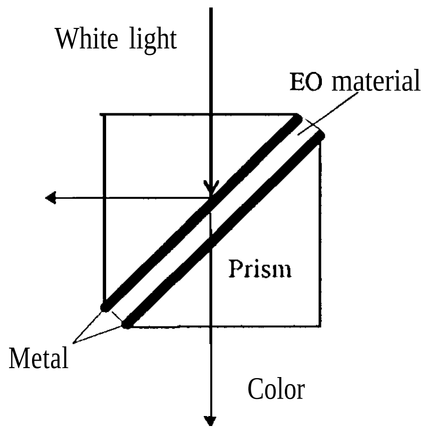

Fig. 1 structure of SPTF using EO material.

In 1996, surface plasmon tunable filter (SPTF) using coupled SP waves to select a transmission spectrum was invented at JPL[7]. The structure of SPTF is shown in Fig. 1. Here a symmetric geometry of metal/EO/metal is employed. Two high index glass prisms are used for the coupling. A thin metal film is evaporated on each prism respectively. A thin EO material layer is sandwiched by the two prisms. The thickness of EO material layer is less than one wavelength.

When a SP wave is excited on one side of metal/EO material interface by the incident photons, the energy of resonance photons will be converted into the motion of free electrons of the metal film, the optical field will penetrate the thin EO layer and excite another SP wave with the same frequency at the other EO/metal interface because of the symmetric structure. The resonance photons will then be re-radiated out as the transmitted light. When a voltage is added on the EO material, the index of the EO material will change, the SP resonance frequency will change, and the transmission spectrum will change. Theoretical calculation shows that for two silver film separated by a 150 nm EO material layer, when the index of the EO layer has a change from 1.5 to 2.0, the transmission peak shifts from 450 nm to 650 nm[8,9].

The coupling mechanics also can be changed by varying the thickness of the dielectric layer between the two metal films. Fig. 2 shows a structure of SPTF using a changeable air gap to selective the transmission spectrum. Here two "T" shaped glass micro-prism plates are separated by pizeo-electric spacers. The two micro-prisms are coated with metal film, and there is an air gap between the two metal films. When a voltage is applied on the pizeo-electric spacer, the length of the pizeo-electric spacer will change, thickness of the air gap will change, and the peak transmission of the transmission will shift.

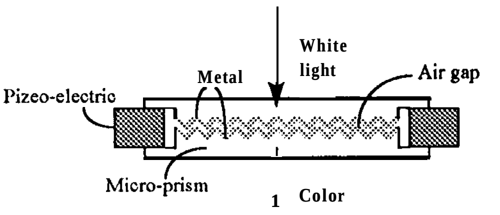

Fig. 2 Structure of SPTF using a changeable air gap.

Fig. 3 shows the theoretical calculation of the tuning ability of the air gap SPTF using silver as the metal film, when the thickness of the air gap changes from 300 nm to 5000 nm, the peak transmission shifts from 400 nm to 1600 nm.

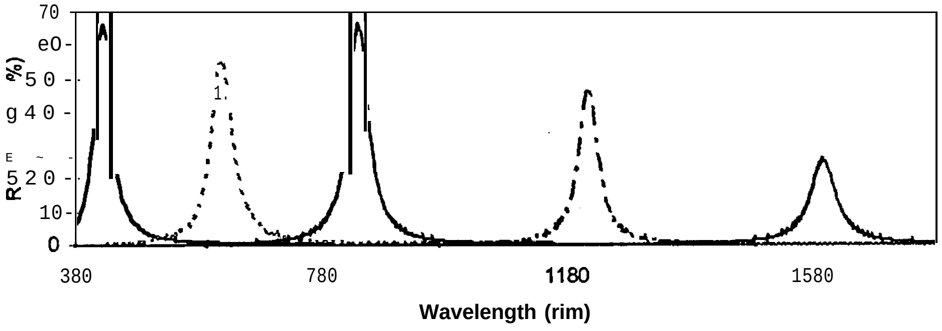

Fig. 3. When the thickness of air gap changes from 300 nm to 5000 nm, the peak transmission of SPTF changes from 400 nm to 1600 nm.

Though the structure of the air gap SPTF is somehow similar to the Fabry-Perot filter, the physics is totally different, the photons are incident at the angle bigger than the critical angle, and two metal films must be used to generate the SP resonance. Also notice the tunable range runs from 400 nm to 1600 nm, is not limited by 2X as the Fabry-Perot filter requires.

The bandwidth of SPTF depends on the choice of metal. The dielectric constant of metal has a real part and on imaginary part, and the imaginary part will control the bandwidth of SPTF.

If the glass material is chosen so that its thermal expansion matches the thermal expansion of the piezo-electric material, this device will be able to work in a wide temperature range, from -200 to over +200 ‘C. The band width of the SPTF can be adjusted by choosing the metal; metals with small imaginary parts of optical constant will have a narrower bandwidth and a higher transmission peak.

Compare with an acoustic-optic tunable filter and liquid crystal tunable filter, SPTF is light weight, low power, and able to work in a wide temperature range.

Active pixel sensor (APS) technology was invented by Eric Fossum at JPL, and now is considered as the next generation solid state image sensors to replace charge coupled device (CCD)[10] for many applications. APS is a low power, light weight, low cost device, it is fabricated by the standard complimentary metal oxide semiconductor (CMOS) technology.

In an APS, both the photodector and readout amplifier are integrated within the pixel. The voltage or current output from the cell is readout over X-Y wires instead of using a shift register. APS can be operated in low voltage (3-5 volts) while CCDS usually need over 25 volts because the need of different clocking voltages. APS uses the standard CMOS technology, therefore the integrated timing and control electronics, sensor array, signal processing electronics, analog to digital converter and interface can be built in a single chip to form a camera-on-a-chip.

JPL has developed an APS camera-on-a-chip using standard CMOS technology that has achieved nearly the same performance as a CCD image sensor but much smaller (< 3.5 cm^3) and less power (< 0.05 w). In comparison, CCDS need several Watts to operate. The dynamic range of APS is over 75 db and noise typically 10 e- rms. With the technology of micro-wedge optical concentrator developed at JPL[11], the fill factor of APS can be as high as over 95%. Now an APS chip using 0.7 μ design rule has been fabricated, the scaled pixel is 11.9 μ x 11.9 μ, and on chip analog-to-digital converter is under development.

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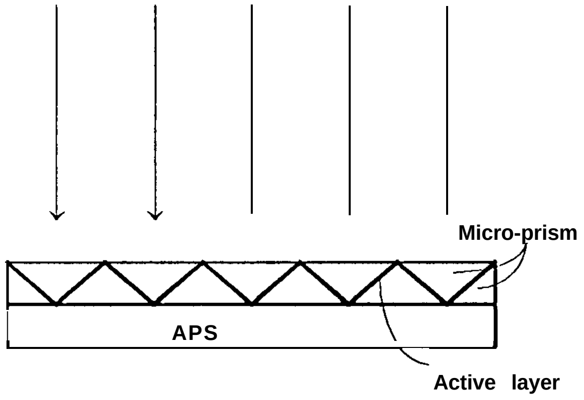

Fig. 4 Spectrometer -on-a-chip using SPTF and APS.

Both being light weight, lower power device, SPTF and APS can be integrated together to build a spectrometer-on-a-chip. Fig. 4 shows the structure of an image spectrometer-on-a-chip. An active layer, either an EO layer or a variable air gap, is sandwiched between two micro-prism plates to forma SPTF. An APS is attached to this SPTF. When a voltage is applied on the active layer, the active layer will change its index (if an EO material layer is used), or change its thickness (if an air gap is used). Then the SPTF will select the transmission spectrum, and the APS will record the image. If the active layer is divided into many pixels to match the pixel size of the APS and an active matrix is used to address the pixel of the active layer, the spectrum of each pixel can be adjusted individually.

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